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Vast Area Detection for Experimental Radiochemistry (VADER) at the National Ignition Facility

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Vast Area Detection for Experimental Radiochemistry (VADER) at the National Ignition Facility

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ABSTRACT

At the National Ignition Facility (NIF), the flux of neutrons and charged particles at peak burn in an inertial confinement fusion capsule induces measureable concentrations of nuclear reaction products in the target material. Radiochemical analysis of post-shot debris can be used to determine diagnostic parameters associated with implosion of the capsule, including fuel areal density and ablator-fuel mixing. Additionally, analysis of debris from specially doped targets can support nuclear forensic research.

We have developed and are deploying the Vast Area Detection for Experimental Radiochemistry (VADER) diagnostic to collect shot debris and interact with post-shot reaction products at the NIF. VADER uses quick release collectors that are easily reconfigured for different materials and geometries. Collectors are located ~50 cm from the NIF target; each of up to 9 collectors views ~0.005-0.0125 steradians solid angle, dependent upon configuration.

Dynamic loading of the NIF target vaporized mass was modelled using LS-DYNA. 3-dimensional printing was utilized to expedite the design process. Model-based manufacturing was used throughout.

We will describe the design and operation of this diagnostic as well as some initial results.

Keywords: VADER, National Ignition Facility, NIF, Radiochemistry

1. INTRODUCTION

The National Ignition Facility (NIF) is the world's largest and highest energy laser system. Its 192 lasers converge upon a small, ~10 mm target containing a spherical, 2 mm diameter capsule. The target is positioned near the center of a large 10 m diameter vacuum vessel known as the Target Chamber[1]. The NIF lasers deliver ~1.8 MJ of energy, which can be used to compress fuel within the capsule to pressures and temperatures similar in scale to that found only in the most extreme environments, such as the cores of planets and stars, as well as inside nuclear weapons during detonation. Critical NIF missions include investigation into nuclear fusion ignition, high energy density science (e.g., planetary and stellar research), and nuclear forensics.

The flux of neutrons and charged particles at peak burn in an inertial confinement fusion capsule induces measureable concentrations of nuclear reaction products in the target material.[2] Radiochemical analysis of post-shot debris can be used to determine diagnostic parameters associated with implosion of the capsule, including fuel areal density and ablator-fuel mixing.[3] Additionally, analysis of debris from specially doped targets can support nuclear forensic research.

We have developed and are deploying VADER to collect shot debris and interact with post-shot reaction products at the NIF. VADER uses quick release collectors that are easily reconfigured for different collector materials and geometries. VADER can also house samples of various materials that are shielded from direct shot debris, but are nevertheless exposed to the associated neutron flux. Data collected from VADER have direct application to both inertial confinement fusion and nuclear forensic research.

Figure 1 shows VADER fielded on a diagnostic snout, itself mounted on a DIM (Diagnostic Instrument Manipulator) cart. A DIM is a 2-stage telescoping positioner which allows diagnostics to be inserted into the NIF Target Chamber and pointed toward a target near Target Chamber Center (TCC) at the time of a NIF shot.

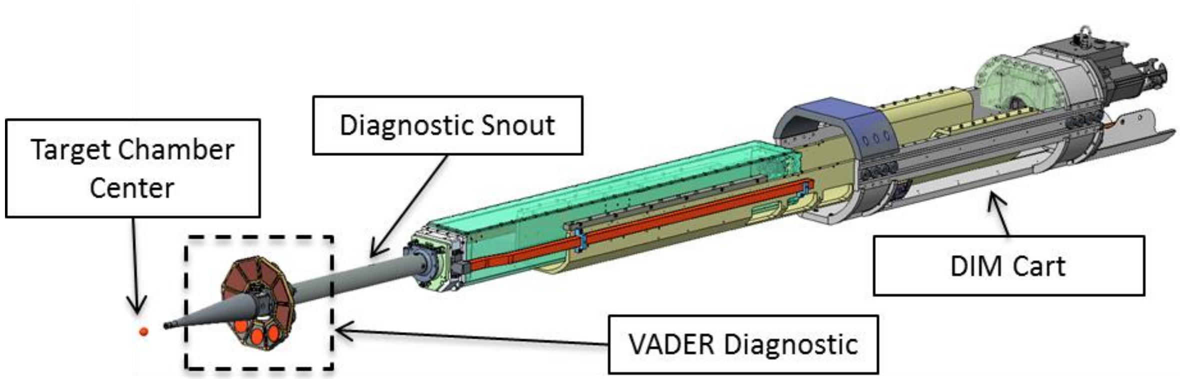


Figure 1. VADER is fielded on a diagnostic snout, itself mounted to a DIM cart and pointed toward a target near NIF TCC, here shown represented by a red pointing volume.

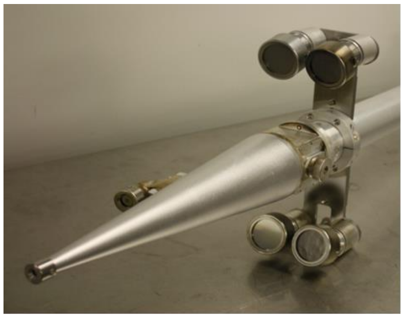
2. SCIENTIFIC MOTIVATION

By collecting shot debris and interacting with reaction products, VADER collectors and samples can be analyzed for a number of purposes, 2 of which are described subsequently.

First, radiochemical analysis can be performed to assess fuel compression performance for inertial confinement fusion experiments. By determining the ratio of the concentrations of (n,γ) and (n,2n) products ($^{198m+g}$Au and ^{196g}Au, respectively)[4], the down-scatter of neutrons in the compressed target fuel can be inferred. Consequently, the fuel areal density and assembly confinement time can be determined, which are indicators of fuel compression performance.

VADER may also be utilized for nuclear forensic research. Following a nuclear event, it may be of interest to determine, by means of forensics, characteristics of the event, such as the type of nuclear device involved. In conjunction with the NIF laser and target, VADER can be used to empirically validate nuclear forensic models by collecting activated material. For instance, by adding a structural material of interest such as steel around the outer surface of a NIF hohlraum (cylinder in which the capsule is contained), unique debris can be created via the laser/target interaction. This debris, containing the activated material of interest, can then be collected by VADER for subsequent analysis. Alternatively, sealed samples of material, such as soil or concrete, can be assembled directly into VADER. Following neutron exposure during a NIF shot, these activated, sealed samples can be analyzed to support nuclear forensic research.

VADER represents the next step in the design evolution of solid radiochemistry collection at the NIF. Figure 2 shows both VADER and an earlier collection design, conventional SRC (Solid Radiochemistry). VADER offers up to ~550% the collection area of conventional SRC by allowing for an increase in total number of collectors (from 4 to 9 simultaneously), as well as the ability to field expanded-area trapezoidal collectors in lieu of the conventional circular design. Where circular collectors feature a collection area of ~1260mm^2 and associated solid angle ~0.005 steradians, trapezoidal collectors feature ~3150mm^2 collection area with solid angle ~0.0125 steradians.



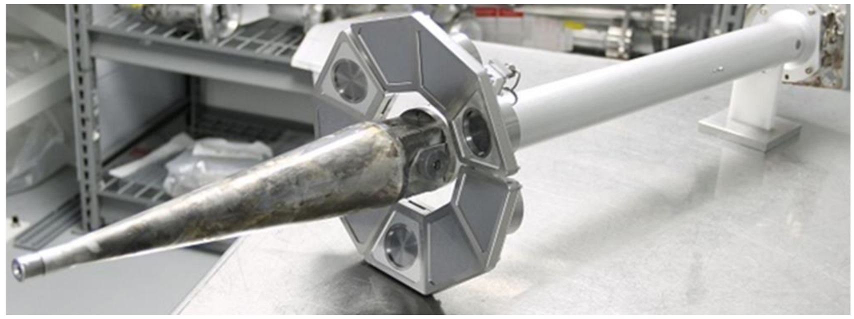


Figure 2. Image at left shows conventional SRC collector design. Image at right shows VADER. Note both conventional SRC and VADER feature circular collectors as shown above. VADER, however, offers the capability to field up to 9 collectors simultaneously, versus 4 for conventional SRC. Additionally, each VADER collector can be run in either a conventional circular collector or expanded-area trapezoidal collector configuration, both of which are shown above.

3. DESIGN

3.1 Mechanical Design

VADER consists of 3 bracket assemblies. Each bracket features 3 ports which can be outfitted with unique collector/sample stacks (Figure 3). The outermost material, referred to as the collector as it captures shot debris directly, can be either an expanded-area trapezoid or a conventional SRC circular design, provided a circular collection adapter is in place. Additional materials may be stacked behind the collector and are referred to as samples, as they are shielded directly from shot debris but nevertheless are subject to the resulting neutron flux. Collector and sample stacks are inserted into trapezoidal ports and positively registered in place by compression springs and bayonet caps. The spring-loaded design provides flexibility by accommodating a variety of collector and sample stack combinations.

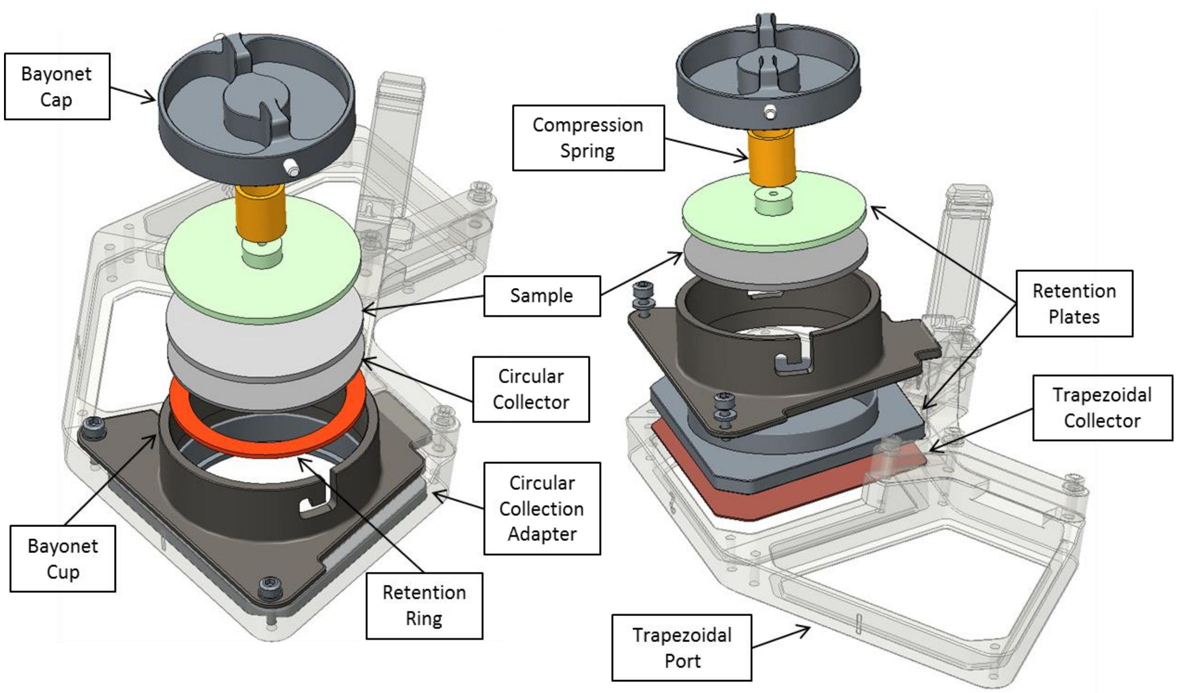


Figure 3. Image at left shows VADER standard circular collector/sample stack. Image at right shows VADER trapezoidal collector/sample stack.

For rapid assembly/disassembly and ALARA (as low as reasonably achievable radiation exposure to workers), all samples and collectors can be removed simply by pressing down and twisting the bayonet cap, which disengages pins from receiving slot hooks in the corresponding bayonet cups (for circular collectors/samples) or removal of 2 fasteners (for trapezoidal collectors/samples).

VADER is mounted to a NIF diagnostic snout by means of a clamping collar (Figure 4). The VADER 2-piece collar assembly is registered and clamped to the snout with captive fasteners and precision pins prior to installation on the DIM cart. Next, up to 3 bracket assemblies are mounted on the collar by means of quick-release connections. These quick-release connections also facilitate rapid assembly/disassembly and ALARA. Because VADER features 3 separate and independent bracket assemblies, certain bracket assemblies can be omitted if line-of-sight interferences exist with other diagnostics on a particular NIF shot. Each bracket features a flange-end stem, which is inserted into a receiving bore in the collar, with the flange-end protruding out the opposite side. A retention clip is then pressed into position around the stem flange-end, and a ball-lock pin is inserted through both the retention clip and collar, providing complete capture of the bracket assembly. The VADER bracket assemblies can be installed on the collar and metrology performed on the entire snout assembly on an offline test stand prior to loading the hardware in a DIM for a NIF shot.

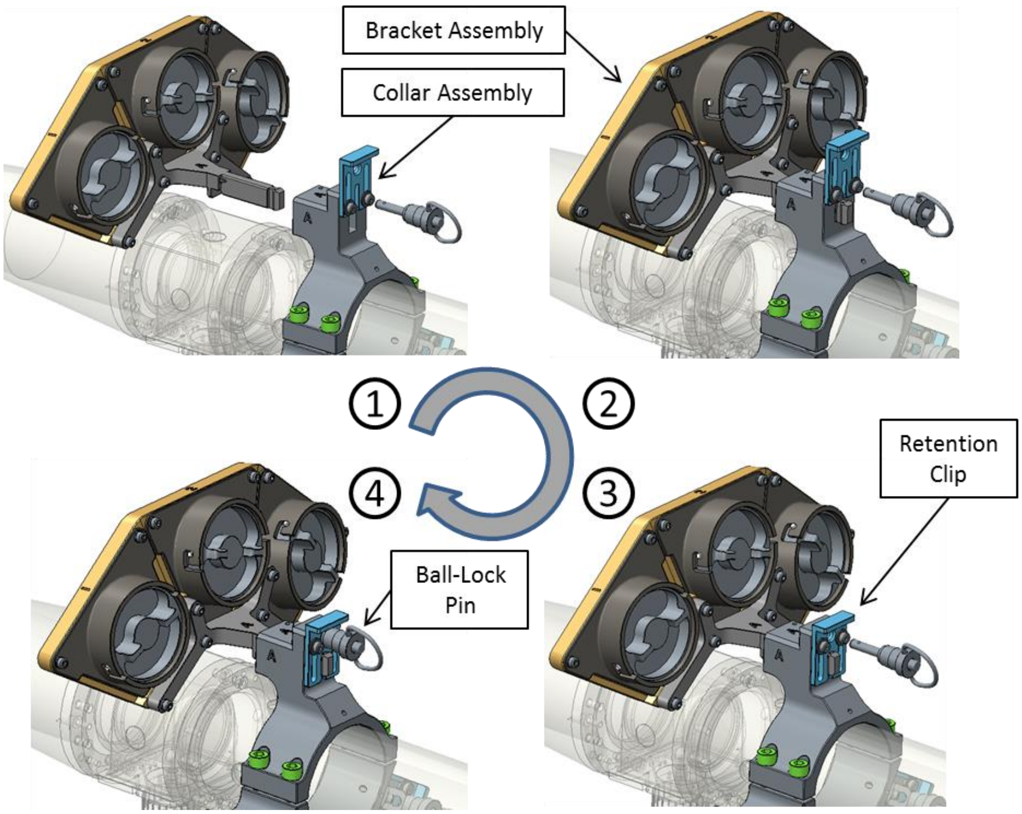


Figure 4. Installation of a VADER bracket assembly is achieved by first inserting the bracket flange-end stem into the collar receiving bore, then engaging both the retention clip and ball-lock pin.

For certain experiments, the locations of individual collectors and samples are critical. To help reduce uncertainty and probability of erroneous placement, the VADER brackets and corresponding collar receiving bores are physically marked with distinct lettering “A”, “B”, and “C”. Additionally, each bracket port is physically marked with distinct numbering “1”, “2” or “3”, resulting in 9 distinct mounting locations A1-C3. Moreover, each bracket stem and associated collar receiving bore is keyed uniquely to prevent incorrect assembly (Figure 5).

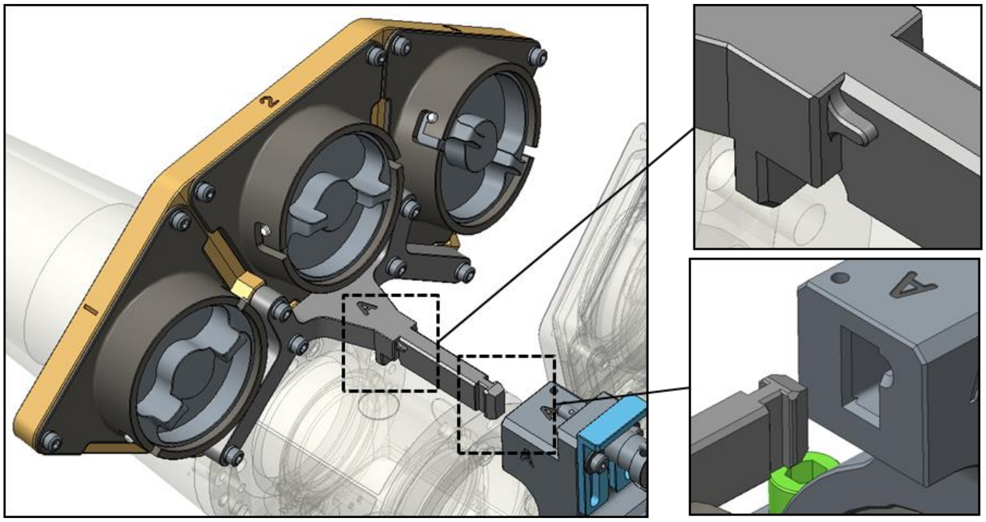


Figure 5. VADER bracket ports are labelled with a distinct alphanumeric combination. Ports A1, A2, and A3 are shown above. Bracket stems and collar receiving bores are keyed to prohibit incorrect installation (e.g., only bracket A can be installed in collar receiving bore A).

Snap-on handling covers are designed to cover the bracket assemblies during handling and transportation (Figure 6). These covers are fabricated from engineering plastic to minimize particulate generation, and feature a 17-4 stainless steel spring hook with plastic wear pad that snaps the cover into place and allows for quick installation and removal.

After careful consideration of potential failure modes, it was determined that the combination of the probability that a handling cover would be inadvertently left installed on a bracket assembly after installation in the DIM, and the resulting effect that the shot data would be compromised and the cover potentially blown off the bracket assembly and into the NIF Target Chamber during a shot presented an unacceptable risk. Therefore, large red tags are tethered onto the covers that read “Remove Before Shot” to reduce the probability of failure mode occurrence.

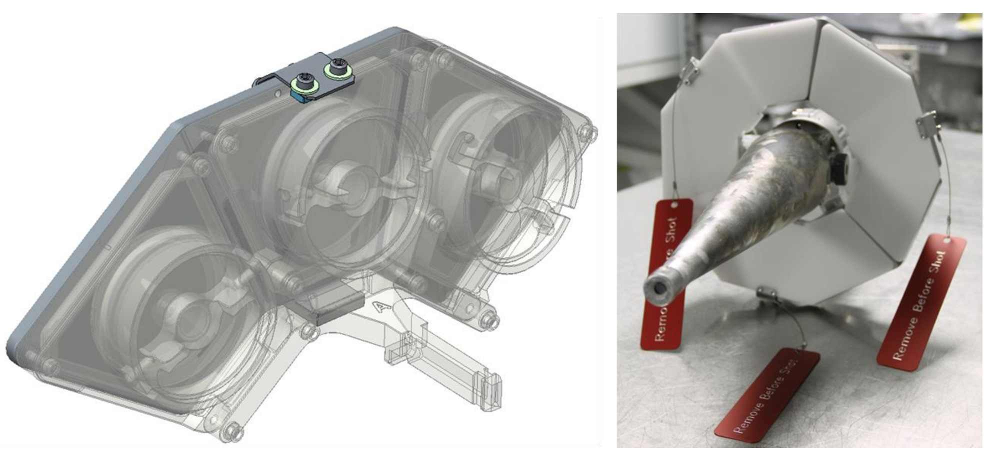


Figure 6. Snap-on transport and handling covers are used to protect critical VADER collector surfaces from damage. Image at left shows model of cover snapped into position with bracket assembly in relief. Image at right shows fielded hardware, where large red “Remove Before Shot” tags are included to ensure covers are removed prior to exposure to a NIF shot.

3.2 Analysis

During a NIF shot, VADER is subject to a dynamic load known as the "debris wind", which is analogous to a brief, high-pressure explosive blast initiating from the target. In order to assess the structural adequacy of the VADER hardware, a dynamic finite element analysis was performed in LS-DYNA (Figure 7). A design with a margin to yield criterion was accepted, and structure-critical components subject to significant bending, shear, and shock loads (e.g. brackets) were specified to be fabricated from ductile materials (e.g. 304 stainless steel). The ductile material selection provided additional confidence by allowing greater margin to ultimate failure. The dynamic finite element analysis also allowed for optimization of the stiffness and preload compression of the bayonet cap spring.

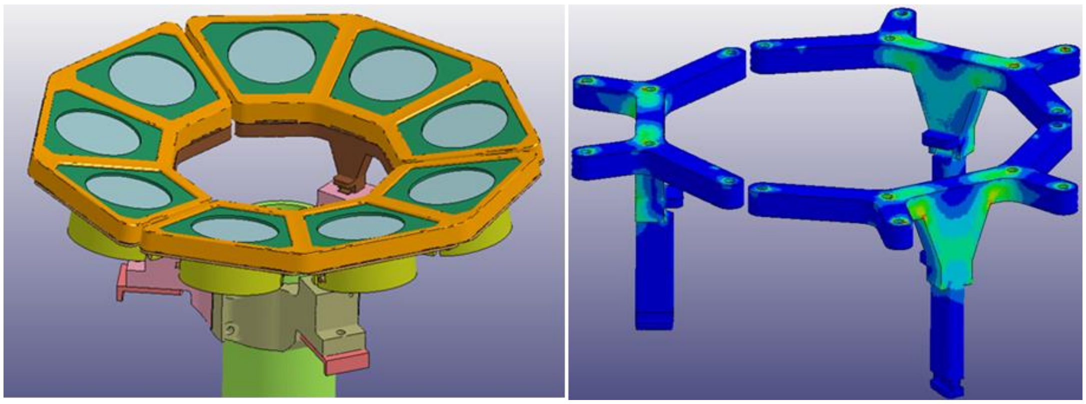


Figure 7. The VADER hardware was modeled with dynamic finite element analysis in LS-DYNA. Loads simulating the NIF debris wind were applied. The finite element model is shown at left. An example resulting von Mises stress field for the VADER brackets is shown at right.

3.3 Streamlined Approach

A rapid-prototype, 3-dimensional printed plastic model of VADER was utilized during the preliminary and intermediate design cycles. During the final design review, the prototype model was used to physically demonstrate assembly and disassembly of hardware in front of an audience of project stakeholders. Moreover, these stakeholders were able to physically handle the prototype hardware, allowing for a more robust and comprehensive understanding of the design sufficiently early in the design cycle to incorporate changes with minimal cost and schedule impact to the project. Additionally, the prototype model was used as part of a concept of operations feasibility study, where the prototype hardware was installed in a mock translucent DIM (Figure 8). This feasibility study was particularly helpful in assessing potential ergonomic and visual line-of-sight issues.

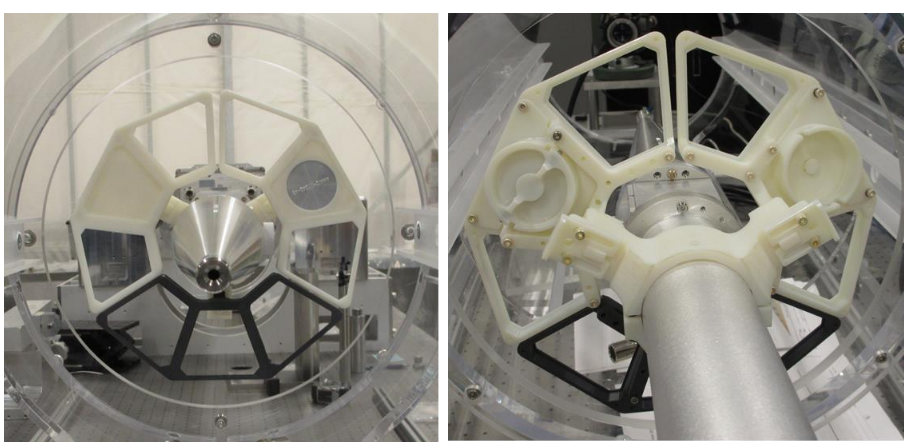


Figure 8. A rapid prototype model of VADER was used for early to intermediate design cycle validation. Here, VADER is shown test fit into a mock translucent DIM.

Model-based manufacturing was utilized for the fabrication of a significant portion of the production VADER hardware. A number of commercial fabricators currently offer quick turn-around (i.e., ~3 business days) model-based manufacturing. These vendors do not require detailed engineering drawings; rather, they utilize computer aided design (CAD) models directly in conjunction with computer numerical control (CNC) machining. Fabrication tolerances vary between vendors, but are often advertised at ±0.005 in. Utilization of model-based manufacturing has the potential to result in significant project cost savings by eliminating the need for fully toleranced engineering drawings and facilitates timely project completion by reducing fabrication lead time.

4. PRELIMINARY RESULTS

VADER was fielded on its first NIF shot on February 26th, 2015. For this shot, 3 conventional circular collectors and 6 trapezoidal collectors were deployed. The system performed mechanically as anticipated, and no significant structural damage was detected as a result of the NIF debris wind loading. Collector stacks exhibited no binding during disassembly.

A modified NIF target was created for this shot consisting of a standard gold hohlraum with thin foils of natural gadolinium, thulium, and neodymium placed around its outside surface. Figure 9 shows views of the modified target as seen from above and by the VADER collectors. Note only the gadolinium foils featured direct line-of-sight with the VADER collectors. Following the NIF shot, the 3 circular VADER collectors (segments A1, B1, and C1 as shown in Figure 10) were counted after the collectors were retrieved via gamma-ray spectroscopy in an HPGe detector. Figure 11 shows the relative intensities of the gamma-ray peaks. The gold isotopes are due to the neutron activation of the gold hohlraum material, which was then collected by VADER. The Gd-159 is produced from Gd-160 (21.86% abundance) via the ^{160}Gd(n,2n)^{159}Gd reaction on the attached gadolinium foils. As shown in Figures 9 and 10, the A bracket collectors are facing the gadolinium foils with the most direct line-of-sight, whereas the B and C bracket collectors are facing other areas of the NIF target. The gamma-ray spectra (Figure 11) indicate that the largest collection of activated gadolinium was on circular collector A1, with B1 having the next highest collection and C1 having the lowest amount of activated gadolinium. These results indicate that collection with VADER is highly directional, and the portion of the target that is in the most direct line-of-sight of the VADER collection segments will be recovered with the highest efficiency.

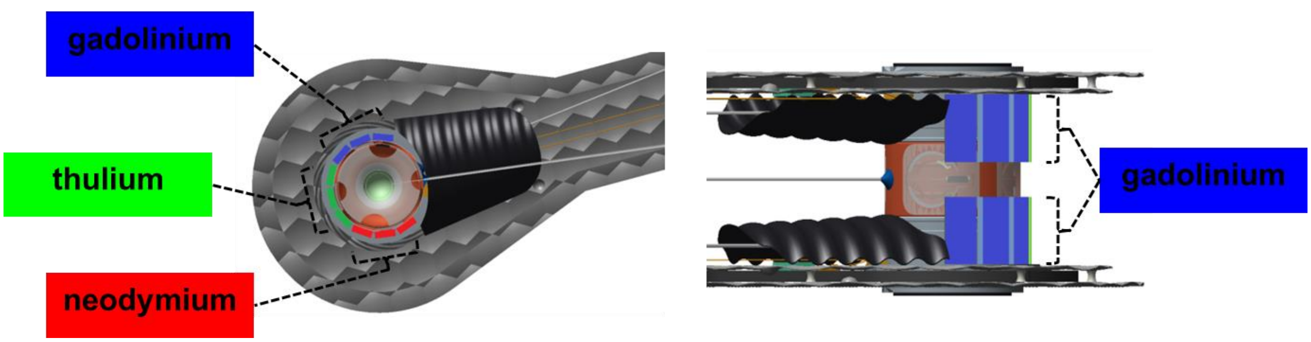


Figure 9. Image at left shows a view of the NIF target from above, with gadolinium, thulium, and neodymium foils shown at top, left, and bottom, respectively. Image at right shows view of NIF target along VADER line-of-sight. Note only gadolinium foils have direct line-of-sight to VADER, and are biased to the right as shown.

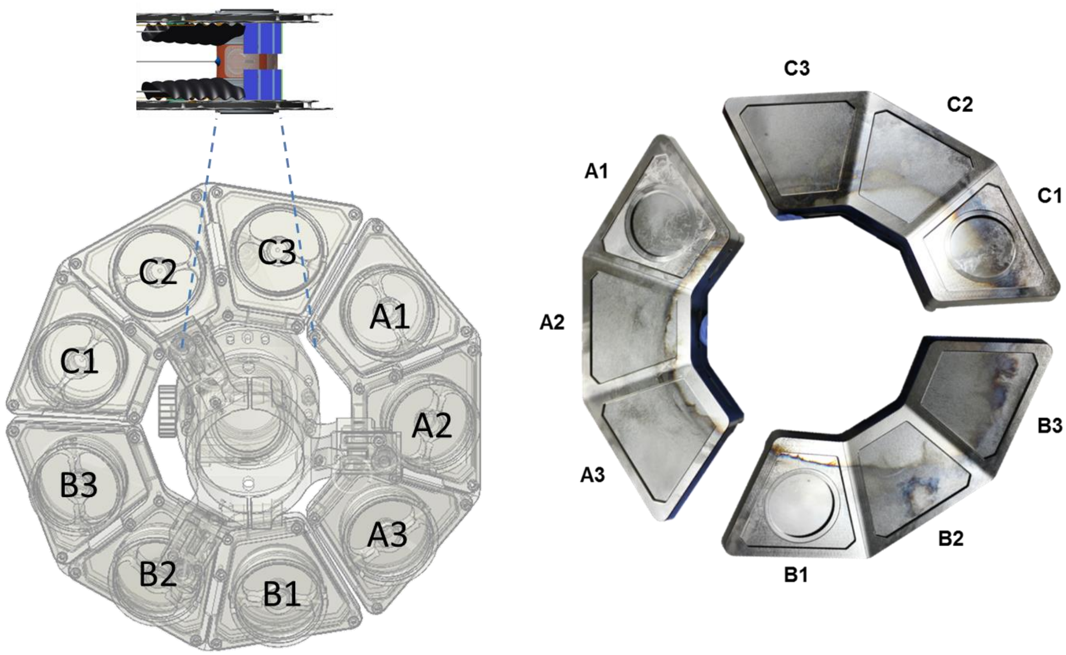


Figure 10. Image at left shows VADER line-of-sight, with NIF target size exaggerated for clarity. Image at right shows VADER collectors post-shot, oriented as viewed from the NIF target. In both views, collectors are labeled with appropriate alphanumeric designation.

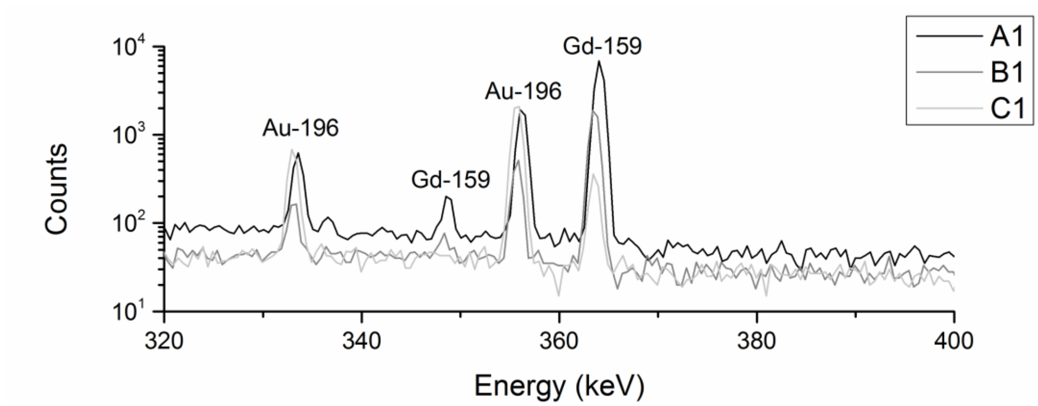


Figure 11. The gamma-ray spectra from the circular VADER collectors A1, B1, and C1 are shown above. The relative intensities represent how much debris was collected on that particular collector. Collector A1, which was directly in the line-of-sight with the gadolinium foils added to the hohlraum, collected the largest amount of activated Gd-159, while collector C1, located the farthest from the gadolinium foils, collected the lowest amount.

While the circular collectors were being analyzed directly via gamma-ray spectroscopy, the trapezoid collectors were chemically processed in order to remove the surface layers containing the collected activated debris. Mass spectrometry was performed on the resultant solutions to determine an absolute collection efficiency for the VADER collectors. Based on initial results, the total fraction of the initial gadolinium that was collected on the individual VADER trapezoidal collectors ranged between 0.1% for the collectors that were on the side opposite the gadolinium line-of-sight up to 1.8% on the A bracket collectors that were directly facing the gadolinium. This further supports the conclusion that VADER collection is highly directional and dependent upon direct line-of-sight.

5. CONCLUSION

VADER was successfully fielded on its first NIF shot on February 26th, 2015. The design, fabrication, and commissioning of VADER validated a streamlined engineering approach, utilizing dynamic finite analysis, rapid prototyping, and model-based manufacturing of production hardware to expedite the engineering process. The results from the initial VADER shot indicated a highly directional debris collection. Moreover, the significantly greater collection area offered by VADER over conventional SRC presents the potential to perform future experiments where detection of trace amounts of debris and/or reaction products would otherwise be difficult or impossible.

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REFERENCES

[1] Moses, E. I., Boyd, R. N., Remington, B. A., Keane, C. J., and Al-Ayat, R., "The National Ignition Facility: Ushering in a new age for high energy density science," AIP Physics of Plasmas 16, 041006 (2009)

[2] Shaughnessy, D. A., Cerjan, C., Moody, K. J., Bernstein, L., Hoffman, R., Stoyer, M. A., Fortner, R., and Schneider, D., "Evaluation of the RADCHEM Diagnostic as an Assessment of Fuel-Abloator Mix and Fuel Rho R," LLNL-TR-472595, March 9, 2011, Lawrence Livermore National Laboratory, Livermore, CA (2011)

[3] Gostic, J. M., Shaughnessy, D. A., Moore, K. T., Hutcheon, I. D., Grant, P. M., and Moody, K. J., "Solid debris collection for radiochemical diagnostics at the National Ignition Facility," AIP Review of Scientific Instruments 83, 10D904 (2012)

[4] Shaughnessy, D. A., Moody, K. J., Gharibyan, N., Grant, P. M., Gostic, J. M., Torretto, P. C., Wooddy, P. T., Bandong, B. B., Despotopulos, J. D., Cerjan, C. J., Hagmann, C. A., Caggiano, J. A., Yeamans, C. B., Bernstein, L. A., Schneider, D. H. G., Henry, E. A., and Fortner, R. J., "Radiochemical determination of Inertial Confinement Fusion capsule compression at the National Ignition Facility," AIP Review of Scientific Instruments 85, 063508 (2014)